

The Space Density of Galaxies through $\mu_{\text{B}}(0) = 25.0 \text{ mag arcsec}^{-2}$

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ABSTRACT

Using the catalog of O’Neil, Bothun, & Schombert (1999), we examine the central surface brightness distribution ($\phi(\mu_B(0))$) of galaxies in the $22.0 \leq \mu_B(0) \leq 25.0$ mag arcsec⁻² range. Taking advantage of having a catalog in which each galaxy has a known central surface brightness, scale length, and redshift, we apply a bi-variate volume correction to the data and extend the surface brightness distribution function by one magnitude, to 25.0 B mag arcsec⁻². The result is a flat (slope = 0) surface brightness distribution function from the Freeman value of 21.65 ± 0.30 to the survey limit of 25.0 mag arcsec⁻², more than 11σ away. This indicates that a significant percentage of the baryonic content of the universe is likely in potentials only dimly lit by the embedded galaxy.

Subject headings: galaxies: luminosity function – galaxies: statistics – galaxies: low surface brightness

1. Introduction

Our ability to detect objects in the Universe has been likened to standing in a well-lit room in the middle of the night, and trying to look through the window to describe the garden 100 yards away. Although it may be possible to definitively say that the garden exists, and even describe some of the large, well-defined plants, coming up with a quantitative description of the fainter, or smaller, or more distant plants is an extremely difficult task. Moreover, of primary scientific interest is not the garden itself, but rather the evolutionary history of the plants that occupy it. With only this one view of the garden available to us, it would be extremely unlikely that our derived evolutionary history would be very accurate. The parallel between the garden and galaxy detection should be clear. In 1965 Arp attempted to quantify this limited view of the universe by defining a “band of visibility,” outside of which we are unable to discern galaxies, due to either the galaxies small apparent size or optically diffuse nature. Arp’s argument was later quantified by Disney (1976), showing that the visibility bias was rather severe.

Since Arp’s work was published, we have successfully broadened the “band of visibility” through improvements in both instruments and detection techniques. As an example, the superb angular resolution of HST has allowed for the distinction between true stars and galaxies which appear star-like in lower resolution surveys (*e. g.* Lilly, *et.al.* 1995; Ellis, *et.al.* 1996; Cowie, *et.al.* 1996; Steidel, *et.al.* 1996; Abraham, *et.al.* 1996; Morris, *et.al.* 1999; O’Neil, Bothun, & Impey 1999). The fact that most of these newly resolved galaxies are very far away means that the local Universe is not filled up with little, dinky, high surface brightness galaxies. On the other end of the spectrum, both improvements in detection techniques (i.e. Malin 1978; Schwartzberg, *et.al.* 1995) and the advent of CCD cameras as a tool in observing has allowed for the detection of increasingly diffuse (low signal-to-noise) stellar systems (*e. g.* Impey, Bothun, & Malin 1988; Davies, Phillipps, &

Disney 1988; Dalcanton, *et.al.* 1997; Schombert & Bothun 1988; O’Neil, Bothun, & Cornell 1997; Matthews & Gallagher 1997). Indeed the recent detection of extremely low surface brightness (LSB) dwarf spheroidal galaxies around Andromeda by Armandroff, Davies, & Jacoby (1998) is consistent with the local Universe having a large population of low mass, nearly invisible galaxies. The Andromeda discovery underscores the severity of surface brightness selection effects. Where once the Milky Way stood alone in the Local Group as a unique host of 7 LSB dwarf spheroidals, we now have detected an apparently equivalent population around M31.

As new observational techniques broaden the visibility band, thus allowing new objects to become detected, the issue shifts from an existence proof to establishing the true space density of these newly discovered galaxies. In establishing this, we must understand the survey limitations. To compensate for these limitations, corrections must be made for the decreased probability of detecting a galaxy the closer it lies to the survey limits. The mathematical formalism of this correction has been both extensively discussed in the literature over the last 20 years (i.e. Disney 1976; Disney & Phillipps 1983; McGaugh 1996; de Jong 1996), and applied to the available data (i.e. McGaugh, Bothun, & Schombert 1995; de Jong 1996). These preliminary applications suggest that the space density of galaxies as a function of their central surface brightness as measured in the blue ($\mu_B(0)$) is relatively flat or at most slow falling out to $\mu_B(0) = 23.5$ B mag arcsec⁻². However, Dalcanton *et.al.* 1997 present data which suggests that space density continues to rise pass this limit. We emphasize that these results refer exclusively to *non-dwarf* galaxies; i.e. those objects with scale lengths larger than ~ 1 kpc.

In this paper we use the sample of LSB galaxies in the O’Neil, Bothun and Schombert (1999) catalog to determine the surface brightness distribution function from a $\mu_B(0)$ of 22.0 B mag arcsec⁻² through 25.0 B mag arcsec⁻² (the catalog limits). In addition to

extending the known distribution by at least one mag arcsec⁻², the O’Neil, Bothun, & Schombert survey has the advantage of having both well defined survey limits and known $\mu_B(0)$, scale lengths, and redshifts, allowing for the use of a bivariate correction for the survey selection and the accurate determination of the surface brightness distribution function in the 23.0 – 25.0 B mag arcsec⁻² range. The paper is laid out as follows: Section 2 describes the volumetric correction applied to the data, section 3 discusses the overall form of our determined surface brightness distribution, and section 4 briefly describes the implications of these results.

2. The Volume Correction

As has often been discussed, detecting high surface brightness (HSB) galaxies within a survey is considerably easier than detecting low surface brightness (LSB) galaxies (i.e. Freeman 1970; Disney 1976; Disney & Phillipps 1983; McGaugh, Bothun, & Schombert 1995; Davies 1990; de Jong 1996; Bothun, Impey, & McGaugh 1997; Dalcanton *et.al.* 1997). Thus determining the true (underlying) surface brightness distribution of a sample of galaxies requires accounting for the probability of a galaxy being detected by a survey of a given design. For a field galaxy survey, the probability of detection is determined simply by the available volume which can be sampled for a galaxy of a given size and luminosity (e.g. its surface brightness). The volume corrected surface brightness distribution is thus

$$\phi(\mu_0) = \sum_{i=1}^N \frac{S^i}{V_{max}^i} \quad (1)$$

where i is summed over all N galaxies in the sample, S^i is 0 or 1 depending on whether a galaxy lies within the described volume, and $V_{max} = \frac{4\pi}{3}d_{max}^3$, the maximum volume in which a galaxy could be detected.

For a surface brightness limited sample (i.e. the catalog of O’Neil, Bothun, & Schombert

1999, OBS from now on) d_{max} can be found by requiring that the diameter of the galaxy be equal to, or greater than, the minimum detectable diameter ($\theta = 2r \geq \theta_l$). For a galaxy with an exponential surface brightness profile this gives:

$$\mu(r) = \mu_0 + 1.086 \frac{r}{\alpha} \quad (2)$$

$$\theta = 2r = 1.84 \alpha (\mu_l - \mu_0) \propto \frac{h}{d} (\mu_l - \mu_0) \quad (3)$$

$$d_{max}(\mu_0) \propto \frac{h}{\theta_l} (\mu_l - \mu_0). \quad (4)$$

where $\mu(0)$ is the central surface brightness of the galaxy, α is its scale length in arcsecs, and h is its scale length in kpcs. Thus, for a surface brightness limited sample,

$$V_{max}(\mu_0) \propto \left(\frac{h}{\theta_l} \right)^3 (\mu_l - \mu_0)^3 \propto \left(\frac{\alpha d}{\theta_l} \right)^3 (\mu_l - \mu_0)^3. \quad (5)$$

3. The Surface Brightness Distribution, $\phi(\mu_0)$

Figure 1 shows the results of applying the correction given in equation 5 to the O’Neil, Bothun and Cornell (1997) data using the redshifts available in OBS. The limiting diameter was set to 25”, and $\mu_l = 25.0$ mag arcsec⁻². This corresponds to an approximate minimum physical diameter of 3 kpc (so again, these are *non-dwarf* galaxies). For the OBS survey, the limiting central surface brightness was found through an extensive series of computer models, in which Monte-Carlo-type simulations of the images were created and searched for galaxies (O’Neil, Bothun, & Cornell 1997). As the true underlying galaxy distribution of the computer-generated images were known, the detection cut-off could be well determined. As such, μ_l , and thus V_{max} for the OBS catalog is extremely well known.

Because the OBS sample is not uniformly distributed in space, but instead follows the same large scale structure as the high surface brightness (HSB) galaxies in the region (i.e. Figure

2 of OBS), performing a V/V_{max} test on the galaxies, and normalizing the distribution function to that (i.e. de Jong 1996) would be extremely difficult and possibly misleading at best. In practice, the OBS sample lies in a shell bounded by radial velocities of 4000 and 12000 km sec⁻¹. The data for this sample, as well as for the comparison samples, have therefore been normalized to one (Figure 1). Additionally, to insure against bias due to under sampling within a bin, the data from OBS was binned to 0.5 mag arcsec⁻². The errors bars for this data are simply \sqrt{N}/N . The low values for the surface brightness distribution between 22 – 23 mag arcsec⁻² are artificial, caused by the 22.0 B mag arcsec⁻² cut-off in the survey sample imposed in the OBS catalog. This was not corrected for.

The data from this survey extends the faint end of the surface brightness distribution function in a horizontal line from 23.0 mag arcsec⁻² through 25.0 mag arcsec⁻², the survey cut-off, matching the predictions made by, *i. e.* McGaugh (1996) and Impey & Bothun (1997). Our distribution does, however, contradict some of the data points of both de Jong (1996) and Davies (1990) in the 23.0 – 24.0 mag arcsec⁻² range, where the de Jong and Davies samples appear to dip downwards.

The first, and most obvious, explanation for the discrepancy between our data and that of both Davies (1990) and de Jong (1996) is that the volumetric corrections for one or more of these samples was done incorrectly, either due to mis-identifying the selection limits of the survey or through poor statistical sampling. The OBS sample is designed to look for galaxies above the 22.0 mag arcsec⁻² range, and is therefore complete through 24.0 mag arcsec⁻², with the uncorrected data having a flat surface brightness distribution from 22.5 through 24.0 mag arcsec⁻² (*i. e.* Figure 8 of O’Neil 1998). Additionally, the surface brightness and diameter cut-off for the OBS sample was determined through computer modeling (O’Neil, Bothun, & Cornell 1997) and therefore is well determined. In contrast, the de Jong sample ranges in central surface brightness from approximately 20.0 mag

arcsec⁻² through 24.1 mag arcsec⁻², with the majority of the galaxies lying in the 21.0 – 22.0 mag arcsec⁻² range. The volumetric corrections for the de Jong sample are concerned only with the diameter limit (θ_l) imposed on the survey and do not account for potential surface brightness selection effects, an omission which de Jong states could cause his survey to be undersampled at the faint $\mu(0)$, large scale length and/or small scale length, bright $\mu(0)$ ends of the spectrum. Combined with the survey's under-sampling in the $\mu(0) > 22.5$ mag arcsec⁻² range, this could result in an artificial drop in the de Jong surface brightness distribution.

Like the de Jong (1996) sample, the Davies (1990) sample is concerned with the entire range of central surface brightnesses, but in this case the total number of galaxies involved in the survey should preclude any difficulties with under-sampling. The Davies sample was corrected for surface brightness selection effects, with a limiting central surface brightness $\mu_{lim}(0) = 25.6$ mag arcsec⁻², and $\theta_l=7''$. This low value for θ_l potentially mixed dwarfs and non-dwarfs together which could greatly confuse the situation. More importantly, no galaxies were actually detected near the defined survey limits. Thus it is entirely possible that the chosen sample limits simply do not accurately reflect the nature of the survey and thus are inappropriate in determining the volumetric correction. This could account for the apparent under-sampling in the 23.25 mag arcsec⁻² bin compared to our data.

Figure 2 show the results of changing the binning for the OBS sample, from bins of 1.0 mag arcsec⁻² through bins of 0.3 mag arcsec⁻². The behavior of the surface brightness distribution as the data becomes undersampled imitates the behavior of the de Jong and Davies samples. It is therefore possible that, as both the de Jong and Davies samples are primarily HSB galaxy samples, they are relatively undersampled in the lower surface brightness regions.

At this point the importance of the chosen value for μ_{lim} should also be noted. Choosing a

value which is fainter (or brighter) than the true survey limits will result in an artificial lowering (raising) of the surface brightness distribution slope at faint μ_0 . This is not surprising as it simply is a statement that if a survey is believed to extend to, say, 26.0 mag arcsec⁻² and yet detects no objects with $\mu_0 \geq 25.0$ mag arcsec⁻², it would be accurate to assume that a fall-off in galaxy number density at faint ($\mu_0 \geq 25.0$) surface brightness is occurring. The OBS sample is no exception to this rule. Were μ_{lim} reduced to 26.0, a slight decline in the slope of the surface brightness distribution function, beginning at 24.0 mag arcsec⁻² would be evident. As μ_{lim} was carefully determined for the OBS sample, though, it should be an accurate representation of the survey's true limitations. With this, and the above, considerations in mind, it is likely the flat surface brightness distribution given by the OBS sample through 24.5 – 25.0 mag arcsec⁻² is an accurate representation of the surface brightness distribution in the local ($z < 0.05$) universe. The implication of such a flat distribution remains profound.

4. LSB Galaxies and the Baryon Fraction

In 1991 Walker, *et.al.* used the latest nuclear cross sections to calculate the baryon abundance (D, ³He, ⁴He, and ⁷Li) within the framework of the standard hot big bang cosmological model. Their calculations led to a nucleon-photon ratio of

$$2.8 \leq n_b/n_\gamma \times 10^{10} \leq 4.0$$

and a baryon density parameter of $\Omega_B h_{100}^2 = 0.0125 \pm 0.0025$. Estimating the known baryon mass density of the universe using $\Omega_B = \Omega_{E/S0} + \Omega_{Sp} + \Omega_{clusters} + \Omega_{groups}$, Persic and Salucci (1992) found $\Omega_B = 2.2 + 0.6 h_{100}^{-3/2} \times 10^{-3}$, showing that 70% – 80% of the predicted baryon mass does not even exist in standard galaxy catalogs.

In their review, Impey & Bothun (1997) speculate that if the M/L of LSB galaxies is

higher than in HSB galaxies, as is indicated in most LSB galaxy studies (i.e. McGaugh & de Blok 1997; OBS), the faint end of the luminosity function has a slope of $-1.6 - -1.8$ (i.e. de Propris, *et.al.* 1995; Bothun, Impey, & Malin 1991), and the central surface brightness distribution remains flat through $28.0 - 30.0$ B mag arcsec $^{-2}$, then the total contribution to the baryonic mass from galaxies is $\Omega_B h_{100}^2 = 0.014 - 0.020$, well within the bounds set by Walker, *et.al.* . Whether the underlying distribution is flat through 28.0 B mag arcsec $^{-2}$ or falls off after 26.0 B mag arcsec $^{-2}$ awaits deeper data to determine. Nevertheless, the results of this study fortify those of McGaugh, Bothun, & Schombert (1995) and McGaugh (1996) and greatly suggest that a lot of baryons are contained in potentials that host very diffuse and hard to detect galaxies.

5. Conclusion

Using a bivariate volume correction, we extend the surface brightness distribution function in a horizontal line from the Freeman value of 21.65 B mag arcsec $^{-2}$ through 25.0 B mag arcsec $^{-2}$, the limit of the OBS catalog. This result is consistent with previous studies (e.g. McGaugh, Bothun, & Schombert 1995; Dalcanton *et.al.* 1997) but extends them to fainter surface brightness levels. Our result is somewhat inconsistent with the findings of two previous surveys in the $23.0 - 24.0$ B mag arcsec $^{-2}$ range (Davies 1990; de Jong 1996). However, our survey was designed specifically to detect galaxies in this surface brightness range and we have quite well defined survey limits (θ_l , mu_l). This leads us to have considerable confidence in our results. It can therefore be said with confidence that LSB galaxies are both important in their own right, and are very significant contributors to the total baryonic mass in the universe.

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FIGURES

Fig. 1.— The volume corrected surface brightness distribution function for all the galaxies in this and other surveys.

Fig. 2.— The effects of under-sampling the data in this survey. The circles, crosses, Xs, and squares result from binning the galaxies in 1.0, 0.5, 0.4, & 0.3 mag arcsec⁻² bins, respectively.